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California Geological Survey Zones of Required Investigation for earthquake-induced landslides - Livermore Valley, California

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ABSTRACT

The California Geological Survey (CGS) recently released the official Seismic Hazard Zones maps of the Altamont, Dublin, and Livermore 7.5-minute quadrangles including the Livermore Valley and surrounding hills (Livermore Valley Study Area). Areas that are most susceptible to seismically-induced landslides are depicted on the maps as Zones of Required Investigation, where site-specific geotechnical investigations are required to be undertaken prior to development.

In establishing the landslide hazard zones, CGS used the best available terrain, geologic, geotechnical, and seismological data. These data are combined in a modified Newmark analysis to identify those slopes with the highest potential for earthquake-induced landsliding. For Dublin and Livermore quadrangles, 5-meter Digital Terrain Models are obtained from Interferometric Synthetic Aperture Radar (IfSAR) where vegetation, buildings, and other cultural features were digitally removed. The resulting bald earth topography is used in generating the slope gradient and slope aspect parameters, and also in updating the boundaries of the different geologic units and existing landslides. Geotechnical data, particularly shear strength, were collected to ascertain the rock strength of the geologic materials. In cases where shear strength data were insufficient to carry out a valid statistical analysis, data from adjacent quadrangles with similar lithology and depositional environment were used in the slope stability analysis.

The data collected and evaluated were transformed into primary and derived GIS layers. Three of the 16 geographic information system (GIS) layers -- Geologic Materials, Landslide Inventory, and Landslide Hazard Potential -- are considered stand-alone maps. In addition to the Seismic Hazard Zones map, the Landslide Inventory layer is also being published as part of CGS's Landslide Inventory Map Series.

INTRODUCTION

Earthquake-induced landslide hazard maps are prepared by the California Geological Survey (CGS) using a GIS that allows the overlaying of various data layers. These data layers include terrain, geologic materials and structure, geotechnical data, mapped landslide features, slope parameters, rock-strength measurements, and probabilistic earthquake shaking estimates. Ground shaking inputs are based upon probabilistic seismic hazard maps that depict peak ground acceleration, mode magnitude, and mode distance with a 10 percent probability of exceedance in 50 years. City, county, and state agencies are required by the California Seismic Hazards Mapping Act (California Department of Conservation, 1997) to use the seismic hazard zone maps in their land-use planning and permitting processes. They must withhold building permits for sites being developed within Zones of Required Investigation until the geologic and soil conditions of the project site are investigated and appropriate mitigation measures, if any, are incorporated into development plans.

The Seismic Hazard Zones maps of the Livermore Valley Study Area (figure 1) covering the 7.5-minute quadrangles of Dublin and Livermore, and Altamont were officially released on August 27, 2008 and February 27, 2009, respectively. They cover the cities of Pleasanton, Dublin, and Livermore, portions of the city of Hayward, and unincorporated areas of Altamont County.

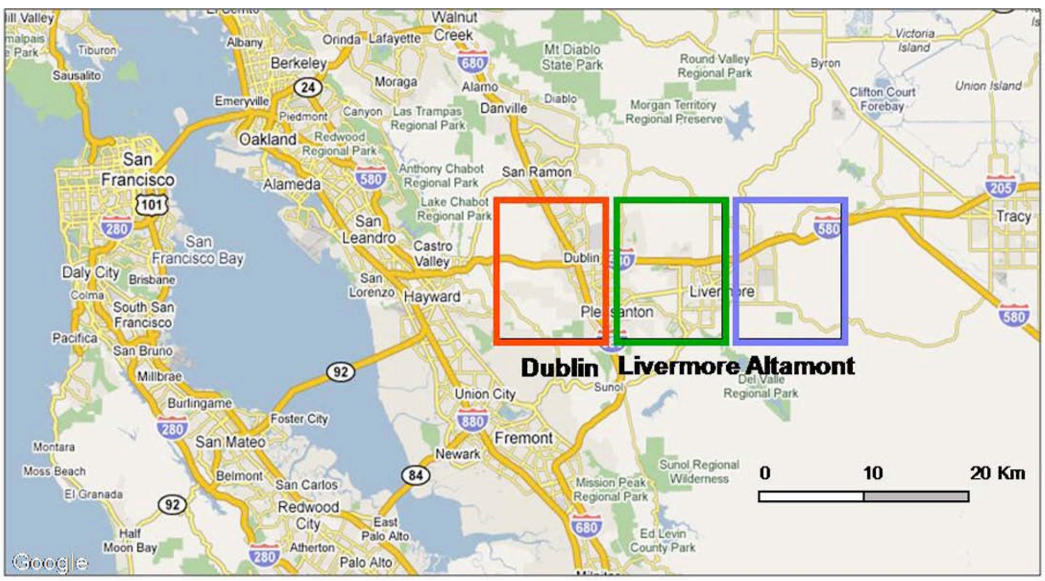

Figure 1. Location Map of the Livermore Valley Study Area encompassing the 7.5-minute quadrangles of Dublin, Livermore, and Altamont, which were mapped for earthquake-induced landslide hazard zones.

A more detailed discussion of the zoning procedures presented in this paper is included in the Earthquake-Induced Landslide Hazard Evaluation Reports of Perez (2008), Wiegers and Perez (2008), and Perez and Haydon (2009), which are available on the California Geological Survey's Internet page: http://www.consrv.ca.gov/cgs/shzp/Pages/Index.aspx.

EARTHQUAKE-INDUCED LANDSLIDE HAZARD ZONING WORKFLOW

Areas that are most susceptible to earthquake-induced landslides are steep slopes in poorly cemented or highly fractured rocks, sloped areas underlain by loose, weak soils, and areas on or adjacent to existing landslides or landslide deposits. These geologic and terrain conditions exist in many parts of California, including numerous hillside areas that have already been developed or are likely to be developed in the future. The opportunity for strong earthquake ground shaking is high in many parts of California because of the presence of numerous active faults. The combination of these factors constitutes a significant seismic hazard throughout much of California, including the hilly areas surrounding the Livermore Valley.

The earthquake-induced landslide hazard zone was derived from the landslide hazard potential map according to criteria developed in a CGS pilot study (McCrink and Real, 1996; McCrink, 2001) and subsequently adopted by the State Mining and Geology Board (California Department of Conservation, 2000). The data collected for the zoning were transformed into primary and derived GIS layers using commercially available software. These layers were combined or merged utilizing different algorithms to extract or generate the needed information or features.

The steps involved in generating the landslide hazard potential map are presented in a workflow diagram (figure 2). At the top of the workflow diagram are four primary GIS layers: Digital Terrain Model (DTM), Bedrock Geology, Geotechnical Data, and PSHA. Sixteen derived layers are generated or extracted from them and near the bottom of the diagram is the Landslide Hazard Potential map. This map is combined with the Landslide Inventory map to generate the Landslide Hazard Zone of required investigation.

The diagram illustrates the hierarchy and interrelation of the various GIS layers. For instance, slope parameters such as slope gradient and slope aspect are features or layers that can be extracted from the digital terrain model. Similarly, dip gradient and dip aspect layers can be extracted from the geologic structure, which in turn was derived from the bedrock geology. Subsequently, adverse bedding can be derived by combining and analyzing (grid overlaying) the categorized slope and dip parameters. A similar procedure is carried out for the other layers.

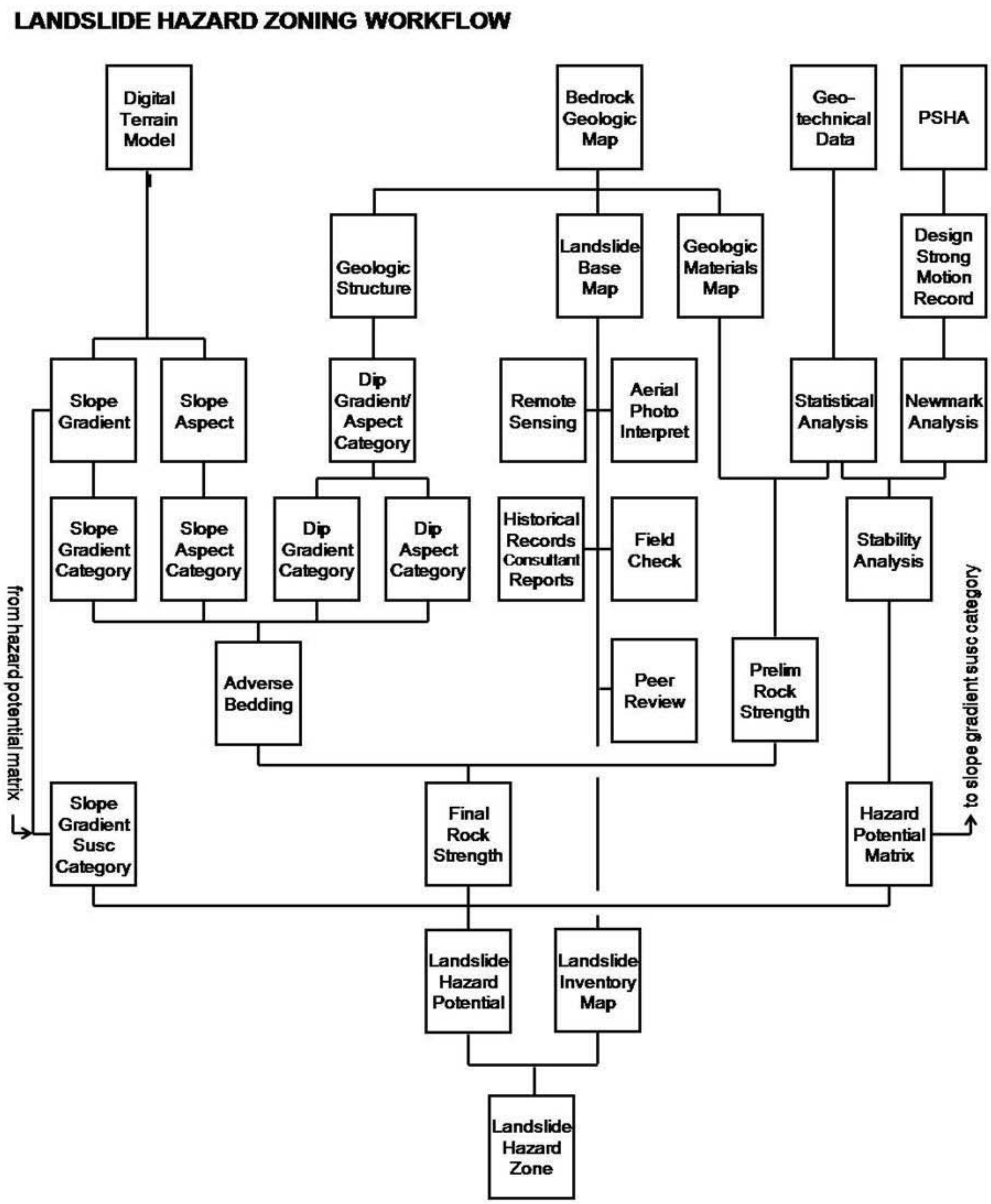

Figure 2. The Earthquake-Induced Landslide Hazard Zoning Workflow Diagram (modified from McCrink, 2001).

GIS DATA LAYERS

The delineation of earthquake-induced landslide hazard zones of the Livermore Valley Study Area is based on the best available terrain, geologic, geotechnical, and seismological data. If unavailable or significantly outdated, new forms of these data were compiled or generated specifically for this area. The following were collected or generated for this zoning:

- Digital terrain data were collected or generated to provide an up-to-date representation of slope gradient and slope aspect in the study area.

- Geologic mapping was compiled to provide an accurate representation of the spatial distribution of geologic materials in the study area. In addition, a map of landslides, whether or not triggered by earthquakes, was prepared.

- Geotechnical laboratory test data were collected and statistically analyzed to quantitatively characterize the strength properties and dynamic slope stability of geologic materials in the study area.

- Seismological data in the form of CGS probabilistic shaking maps and catalogs of strong-motion records were compiled and used to characterize future earthquake shaking within the mapped area.

Terrain Data

The calculation of slope gradient is an essential part of the evaluation of slope stability under earthquake conditions. An accurate slope gradient calculation begins with an up-to-date map representation of the earth's surface in the form of a digital topographic map. For both Dublin and Livermore quadrangles, Digital Terrain Models (DTM) were obtained from Intermap's Interferometric Synthetic Aperture Radar (IFSAR) system. The DTM (figure 3) of the Dublin quadrangle was derived from the original radar data, available as a Digital Surface Model (DSM). Vegetation, buildings, and other cultural features were digitally removed using the company's proprietary software, TerrainFit (Intermap, 2003). This terrain data, which was acquired in 2003, presents elevations at five-meter postings with two meters root-mean-square error (RMSE) horizontal positional accuracy and one-meter vertical positional accuracy. Furthermore, the DTM was resampled using a bilinear method in order to minimize the presence of false geometric artifacts in the radar data. A slope gradient map was generated from the DTM using a third-order, finite-difference, center-weighted algorithm (Horn, 1981). For the Altamont quadrangle, the DTM was derived from the USGS 10-meter Digital Elevation Model (DEM).

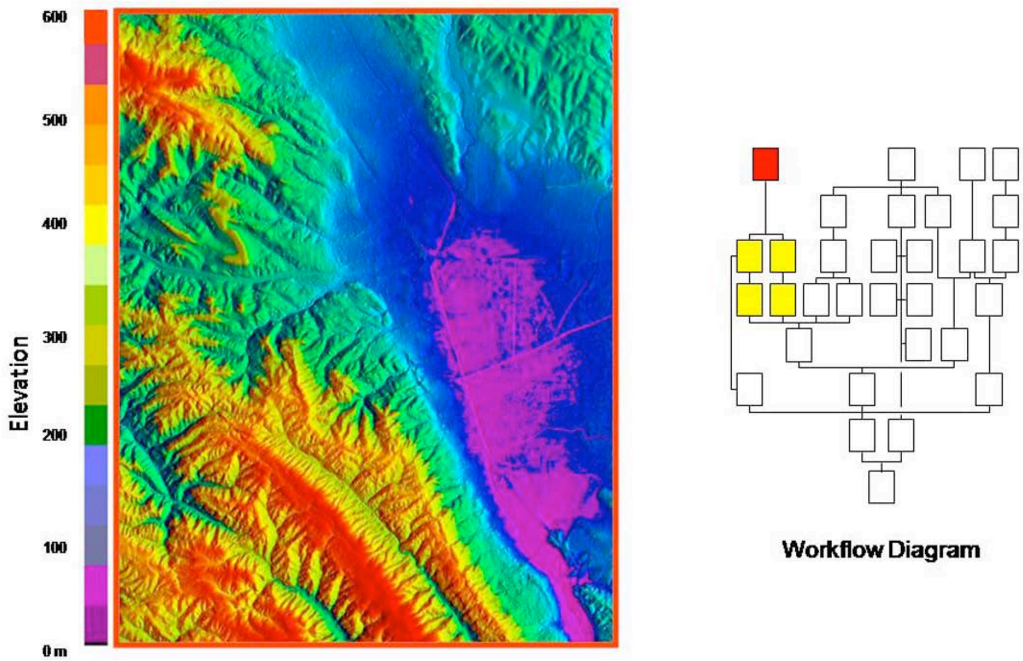

Figure 3. IfSAR DTM colorized hillshade of Dublin quadrangle (red box in the workflow diagram). Derived layers, such as slope gradient and slope aspect (yellow boxes in the diagram) can be extracted from the DTM primary layer.

Geologic Data

The primary sources of bedrock geologic mapping used in the slope stability evaluation of the Livermore Valley Study Area were obtained from U.S. Geological Survey Open File Report OFR 96-252 (Graymer and others, 1996) and the unpublished 1:24,000-scale geologic map recently completed by J.M. Sowers (2006) and the Stockton 1:100,000-scale quadrangle by Graymer (2004). Geologic mapping by Dibblee (1980) was also reviewed. The nomenclature of the Quaternary geologic units was based on U.S. Geological Survey Open File Report OFR 00-444 (Knudsen and others, 2000).

CGS geologists modified the digital geologic map in the following ways: (1) landslide deposits were deleted from the map so that bedrock formations and the newly created landslide inventory would exist on separate layers for the hazard analysis; (2) air-photo interpretation, digital orthophoto quarter-quadrangle review, satellite imagery review, and field reconnaissance were performed to assist in the remapping of contacts between bedrock and surficial geologic units; (3) contacts and distribution of alluvial deposits, as well as active gravel quarries, were modified to conform to 2006 topography as depicted on DigitalGlobe imagery (Google Earth, 2006) and Intermap's Ortho-rectified Radar Imagery (Intermap, 2003); and (4) the relation of the various geologic units to the development and abundance of landslides was noted. Figure 4 is an example of the bedrock geologic map (USGS OFR 96-252) used in the zoning.

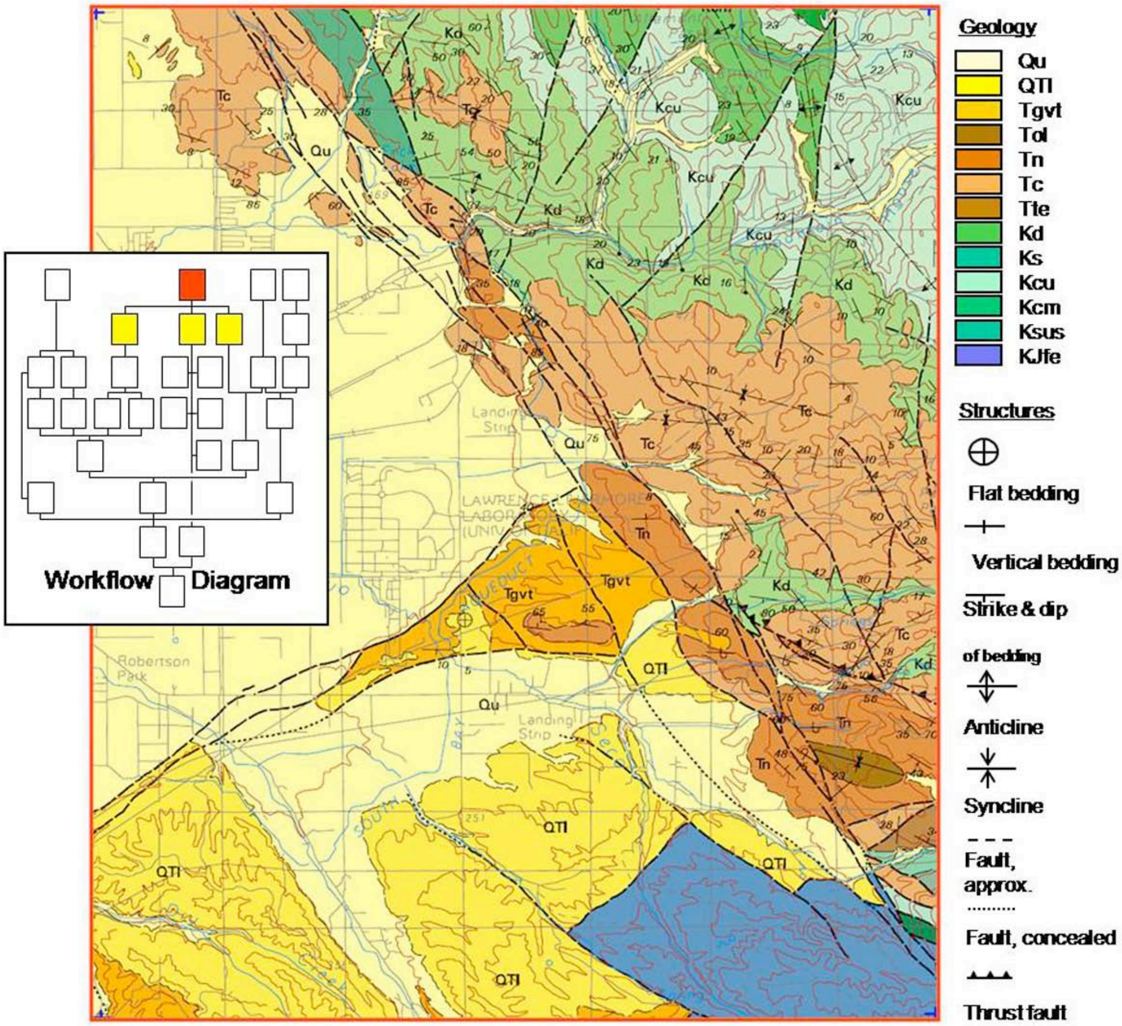

Figure 4. Bedrock geologic map of the Altamont quadrangle (red box in the workflow diagram). Derived layers such as geologic structure, landslide base, and geologic materials (yellow boxes in the diagram) are extracted and modified from this geologic map.

Geotechnical Data

To evaluate the stability of geologic materials under earthquake conditions, the geologic map units are ranked and grouped relative to shear strength. Generally, the primary source for shear-strength measurements is geotechnical reports prepared by consultants, which are on file with local government permitting departments. Shear-strength data for the units identified on the Livermore Valley geologic map were obtained from the cities of Livermore, Pleasanton, and Dublin, from the County of Alameda, and from CalTrans. The locations of rock and soil samples taken for shear testing within the Dublin quadrangle are shown on figure 5.

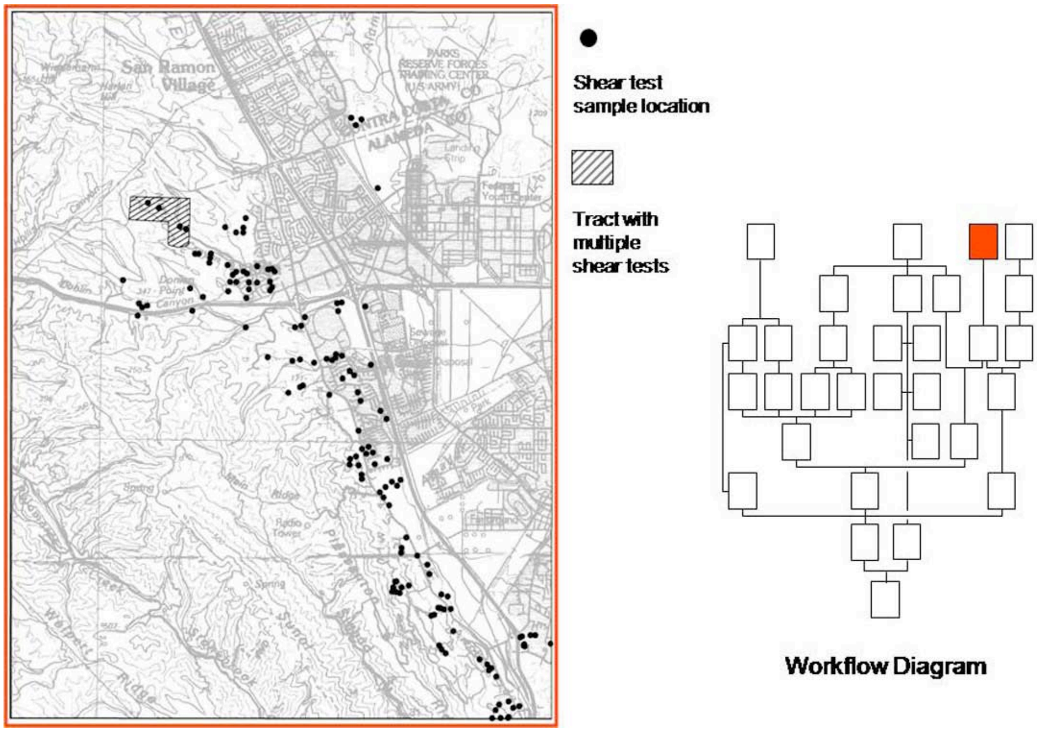

Figure 5. Location map of rock and soil samples where shear testing were undertaken for the Dublin quadrangle. A total of 161 shear tests were collected from the cities of Dublin and Pleasanton and the County of Alameda.

Shear strength data gathered from the above sources were compiled for each geologic map unit. Geologic units were grouped according to average angle of internal friction (average phi) and lithologic character. For each geologic strength group, the average shear strength value was then assigned to each map unit (Table 1) in the Dublin quadrangle, and used in the slope stability analysis. A geologic material-strength map that provides spatial representation of material strength for use in slope stability analysis was developed based on these groupings.

Group 1	Group 2	Group 3	Group 4	Group 5
Kc(fbc)	Kcv(abc)	KuII(fbc), Kcv(abc)	Kc(abc), Kull(abc)	Qls
Ko(fbc)	Tbr(fbc)	Tro(abc), Tt(abc)	Ko(abc), KsVII(abc)	
KsVII(fbc)	Tcs, Ts	Tn(abc), Tc(abc)	sp, Tbr(abc)	
Tbg(fbc)	Tro(fbc)	To(abc), QTl	Tbg(abc), Tusv	
Tbd	Tc(fbc)	Qpa, Qpf, Qoa2, Qoa1	Qoa, Qf, Qhb, Qhff	
Tbe	Tn(fbc)	Qa, Qha, Qhf, Qhc	Qht, Qhty	
Tbi	To(fbc), Tt(fbc)	Af, ac, alf	Qhly, Qhfy	

Table 1. Shear strength groups and map units in the Dublin quadrangle.

Seismological Data

To evaluate earthquake-induced landslide hazard potential in the study area, a method of dynamic slope stability analysis developed by Newmark (1965) was used. As implemented for the delineation of earthquake-induced landslide zones, the Newmark method necessitates the selection of a design earthquake strong-motion record ("design" refers to a representative record) to provide the "ground shaking opportunity." For the Livermore Valley Study Area, selection of a strong motion record was based on an estimation of probabilistic ground motion parameters for modal magnitude, modal distance, and peak ground acceleration (PGA) as depicted in figure 6. The parameters are based on the *2002 California Probabilistic Seismic Hazard Assessment (PSHA) Model* developed jointly by the CGS and USGS (Frankel and others, 2002; Cao and others, 2003) for a 10% probability of being exceeded in 50 years.

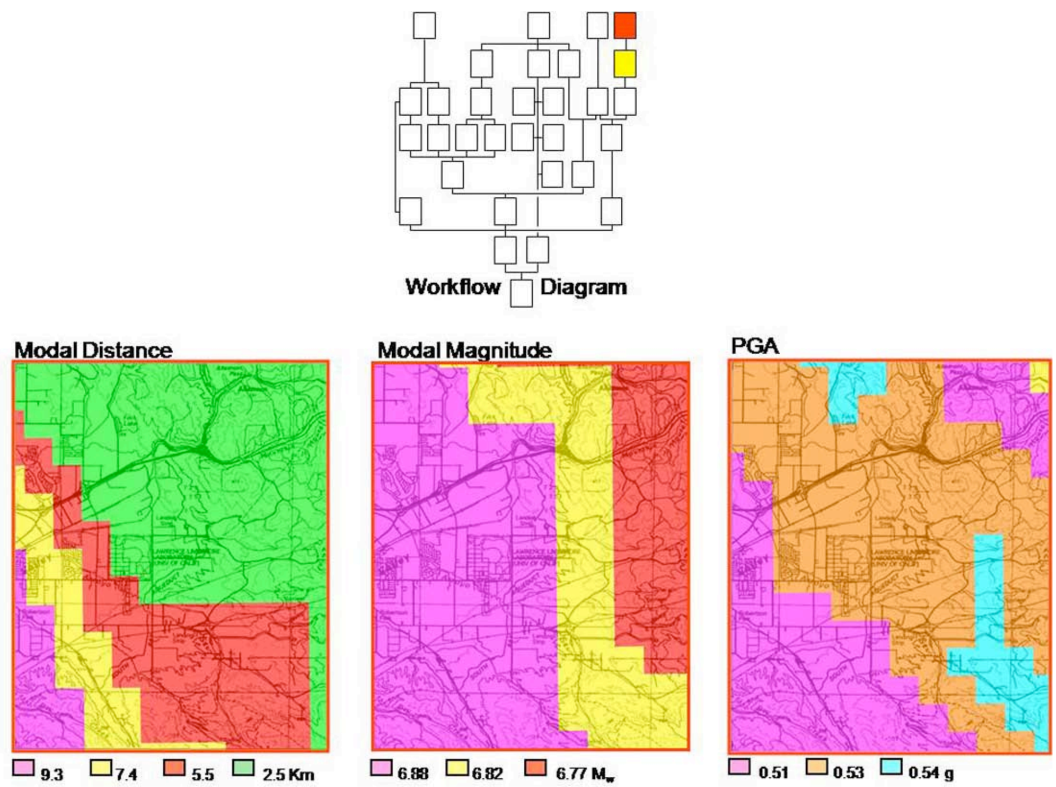

Figure 6. The probabilistic ground motion parameters for modal distance, modal magnitude, and peak ground acceleration used in establishing the strong motion record for Altamont quadrangle.

In the examples given in Figure 6, the parameters used in the record selection are:

Modal Distance	2.5 to 9.9 km
Modal Magnitude	6.8
PGA	0.49 to 0.54 g

The strong-motion record selected for the slope stability analysis in the Altamont quadrangle is the Corralitos record from the 1989 magnitude 6.9 Loma Prieta earthquake (Shakal and others, 1989). This record had a source-to-recording site distance of 5.1 km and a peak ground acceleration (PGA) of 0.64. The selected strong motion record was not scaled or otherwise modified prior to its use in the analysis.

SLOPE STABILITY ANALYSIS

A slope stability analysis was performed for each geologic material-strength group at slope increments of 1 degree. An infinite-slope failure model under unsaturated slope conditions was assumed. A factor of safety was calculated first, followed by the calculation of yield acceleration from Newmark's equation: $a_y = (FS\text{-}1)\ g \sin \alpha$ where **FS** is the Factor of Safety, **g** is the acceleration due to gravity, and **α** is the direction of movement of the slide mass, in degrees measured from the horizontal, when displacement is initiated (Newmark, 1965). For an infinite slope failure, i.e., failure plane is parallel to the ground surface, **α** is the same as the slope angle.

The yield accelerations resulting from Newmark's equations represent the susceptibility to earthquake-induced failure of each geologic material-strength group for a range of slope gradients. Based on the relationship between yield acceleration and Newmark displacement, hazard potentials were assigned as follows:

1. If the calculated yield acceleration was less than 0.086g, a Newmark displacement greater than 30 cm is indicated, and a HIGH hazard potential was assigned.
2. If the calculated yield acceleration fell between 0.086g and 0.133g, a Newmark displacement between 15 cm and 30 cm is indicated, and a MODERATE hazard potential was assigned.
3. If the calculated yield acceleration fell between 0.133g and 0.234g, a Newmark displacement between 5 cm and 15 cm is indicated, and a LOW hazard potential was assigned.
4. If the calculated yield acceleration was greater than 0.234g, a Newmark displacement of less than 5 cm is indicated, and a VERY LOW potential was assigned.

Table 2 summarizes the results of the slope stability analyses. The earthquake-induced landslide hazard potential map (figure 7) was prepared by combining the geologic material-strength map and the slope map according to this table.

Geologic Material Strength Group (Average Phi)	HAZARD POTENTIAL SLOPE (Degrees)			
	Very Low	**Low**	**Moderate**	**High**
1 (32)	0 to 20	21 to 25	26 to 27	>28
2 (26)	0 to 15	16 to 18	19 to 20	>21
3 (23)	0 to 10	11 to 15	16 to 18	>19

Table 2. Hazard Potential matrix for earthquake-induced landslides in Livermore quadrangle.

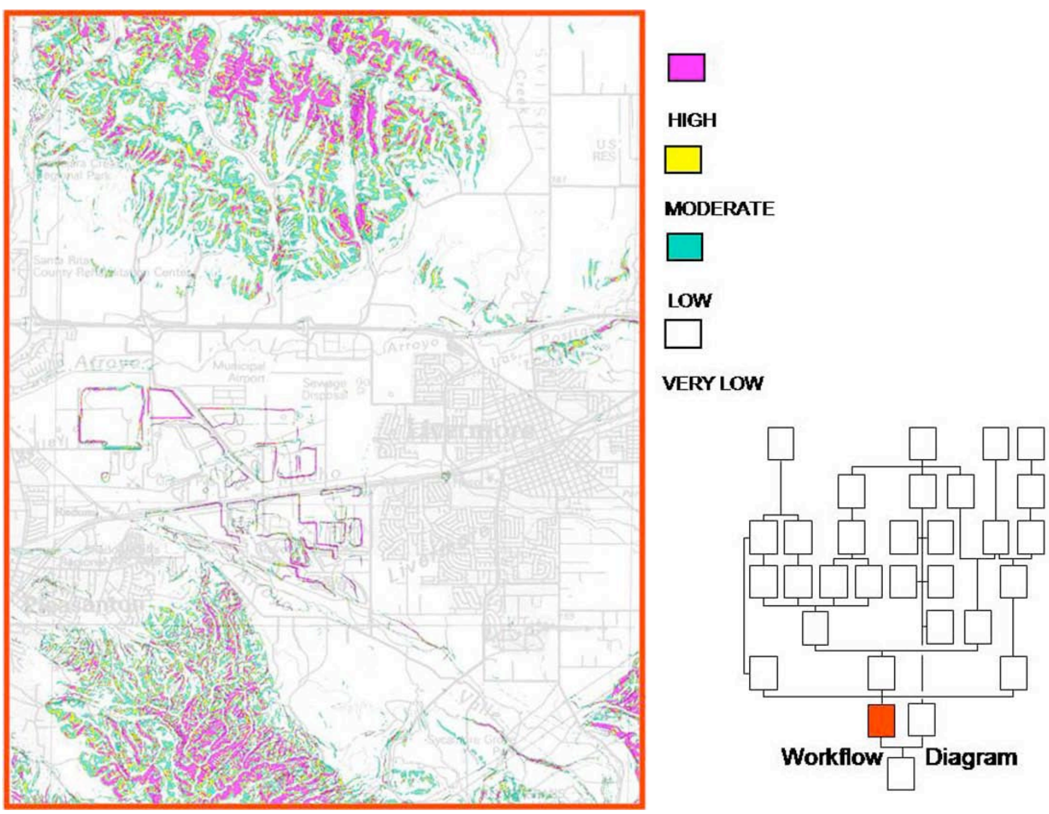

Figure 7. The landslide hazard potential map of Livermore quadrangle showing the different levels of hazard potential (from Very Low to High).

HAZARD POTENTIAL ANALYSIS

Based on the conclusions of a pilot study performed by CGS (McCrink and Real, 1996; McCrink, 2001), CGS designates earthquake-induced landslide hazard zones that encompass all areas that have a High, Moderate or Low level of hazard potential (see Table 2). This would include all areas where the analyses indicate Newmark earthquake displacements of five centimeters or greater. Areas with a Very Low hazard potential, indicating less than five centimeters displacement, are excluded from the zone.

Using Table 2 as an example, all areas characterized by the following geologic strength group and slope gradient conditions are included in the earthquake-induced landslide hazard zone:

1. Geologic Strength Group 3 is included in the zone for all slopes greater than 11 degrees.
2. Geologic Strength Group 2 is included for all slopes greater than 16 degrees.
3. Geologic Strength Group 1 is included for all slopes greater than 21 degrees.

Based on the preceding discussions, Table 3 summarizes the different "geologic strength group-slope gradient" combinations (listed by quadrangle) that fall within the earthquake-induced landslide hazard zone.

Quadrangle	Geologic strength group	Slope (Degrees)	Percent of quadrangle within the hazard zone
Dublin	Gp 4	> 11	33%
	Gp 3	> 19	
	Gp 2	> 21	
	Gp 1	> 24	
Livermore	Gp 3	> 11	19%
	Gp 2	> 16	
	Gp 1	> 21	
Altamont	Gp 3	> 12	22%
	Gp 2	> 17	
	Gp 1	> 22	

Table 3. Hazard potential matrix and percent of land area per quadrangle that are included in the earthquake-induced landslide hazard zone in Livermore Valley.

ZONES OF REQUIRED INVESTIGATION

The landslide hazard potential map (figure 7) is combined with the landslide inventory map to generate the landslide hazard zones of required investigation (figure 8). Figure 9 shows an example of the Official Hazard Zone Map (Livermore Quadrangle). The summary of this paper, presented as a poster at the DMT meeting, is shown in figure 10.

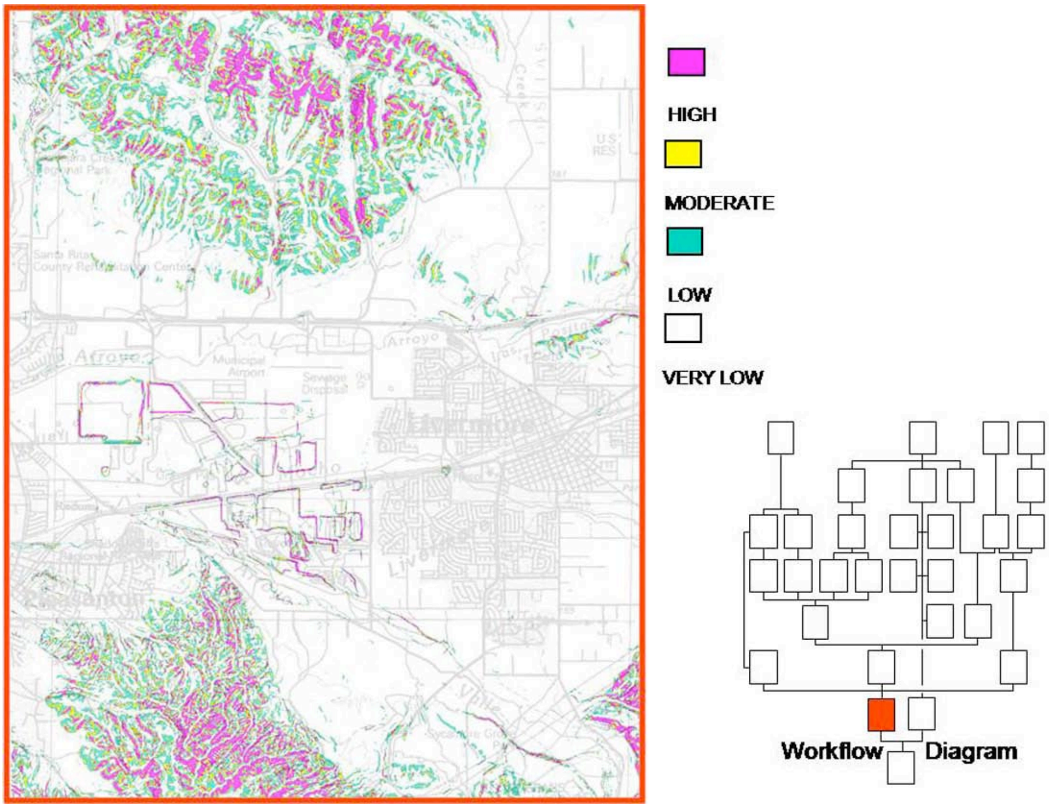

Figure 7. The landslide hazard potential map of Livermore quadrangle showing the different levels of hazard potential (from Very Low to High).

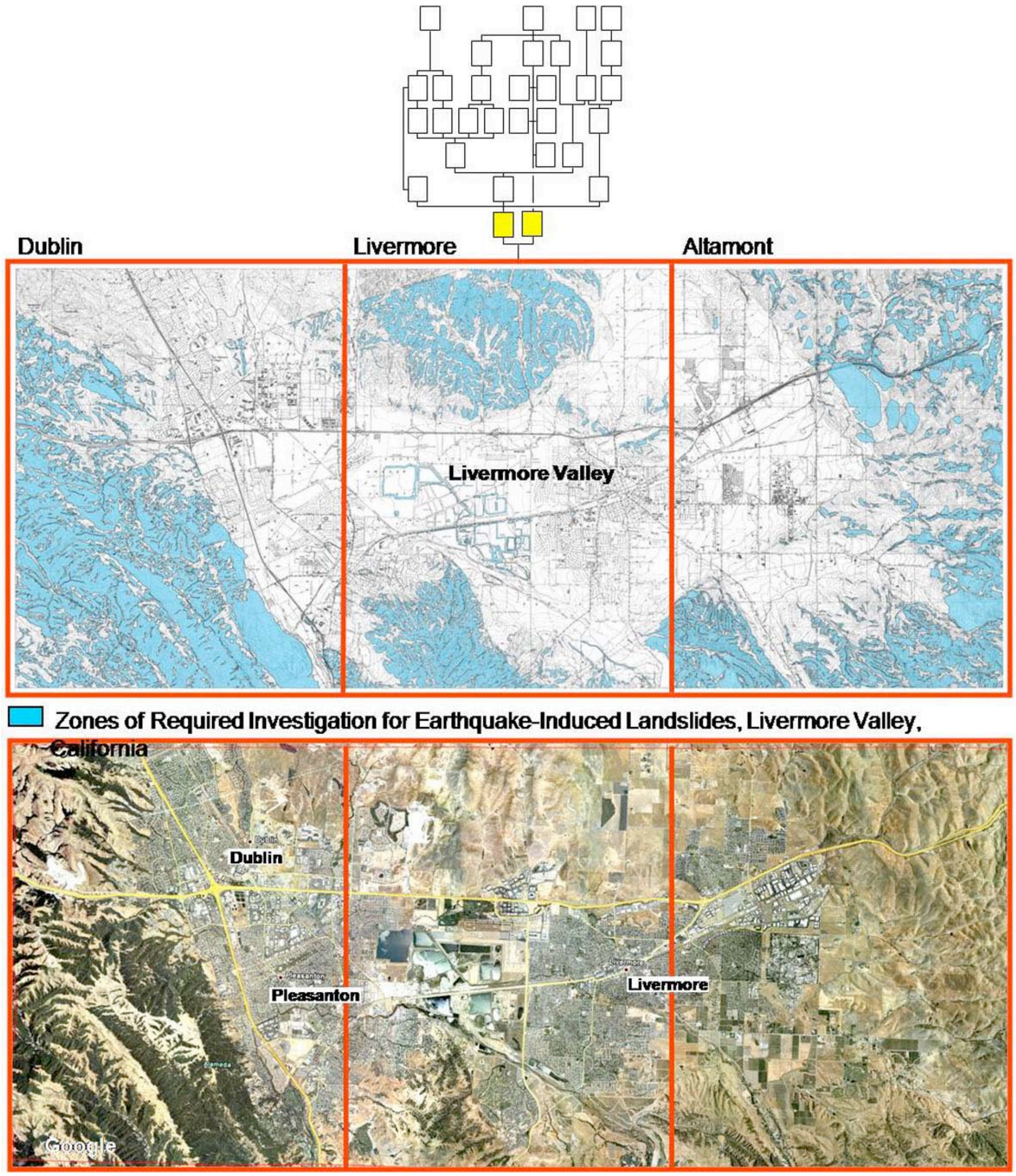

Figure 8. The mountainous and hilly areas surrounding Livermore Valley fall within the zone of earthquake-induced landslide hazard (depicted in blue in the upper image) and represent 32.7% of the entire land area of the three quadrangles. The Google image (lower image) shows the relative location of highway corridors (yellow lines) and built-up areas (cities of Dublin, Pleasanton, and Livermore).

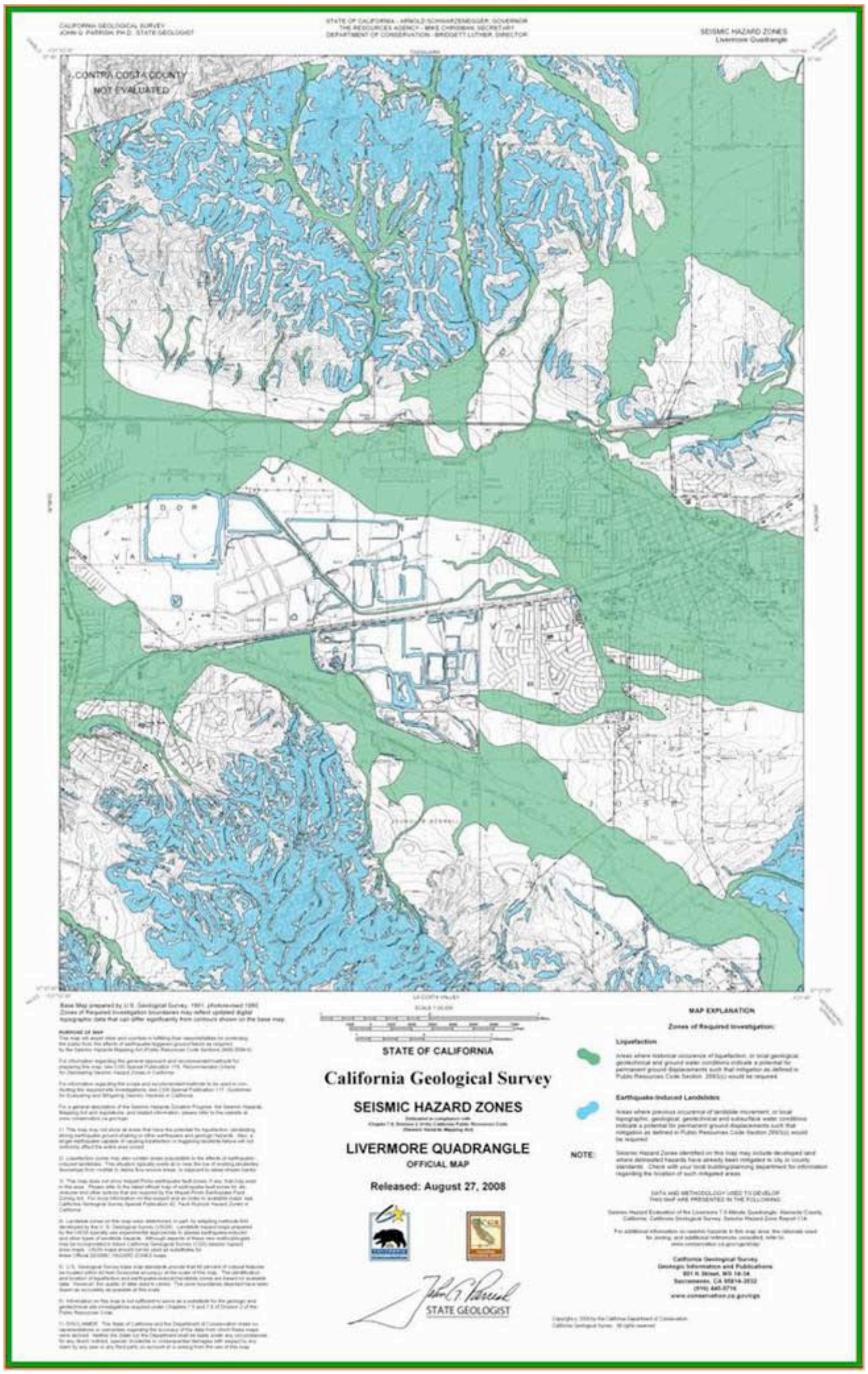

Figure 9. The Seismic Hazard Zones Map of Livermore quadrangle shows both liquefaction (green) and earthquake-induced landslide (blue) zones of required investigation.

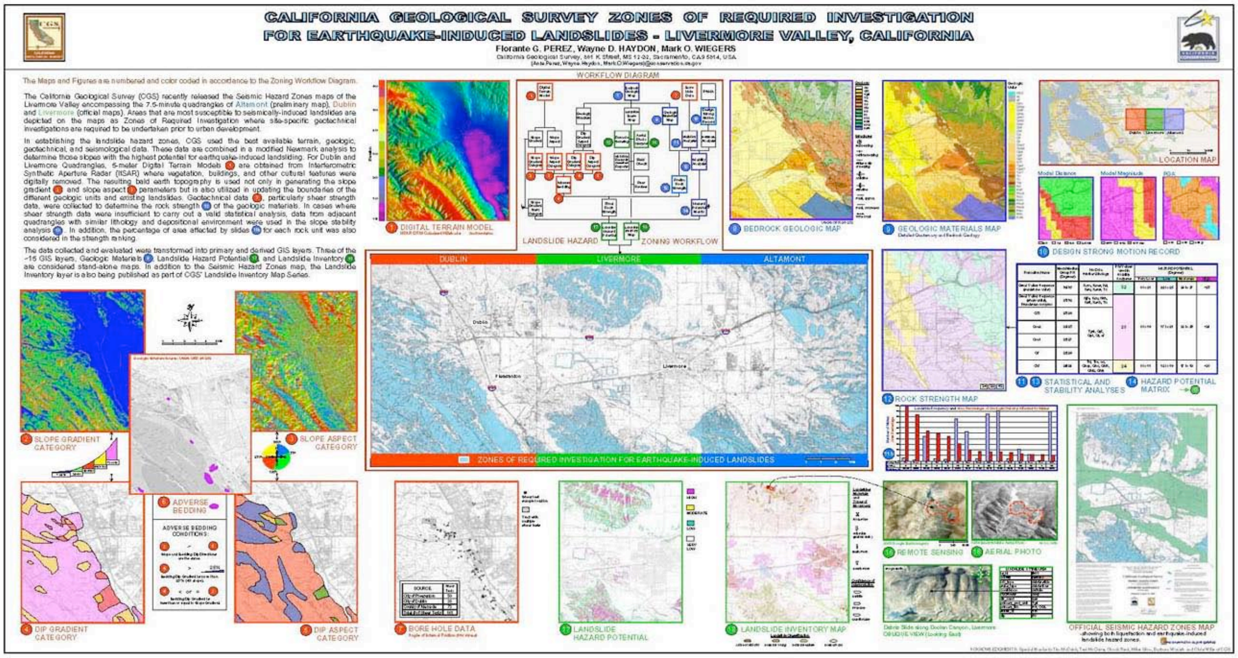

Figure 10. California Geological Survey Zones of Required Investigation for Earthquake-Induced Landslides - Livermore Valley, California (presented as a poster; see full-resolution image at http://ngmdb.usgs.gov/Info/dmt/docs/1perez10.pdf).

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